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Predicting cavitation in tunnel spillways

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A method of calculating the location of cavitation damage in spillways is presented here. This method, together with experience curves, allows damage to be estimated as a function of duration of operation. Procedures are given to design aeration grooves which can protect spillways from cavitation damage.

THE PROBLEM of cavitation damage is not new. As early as 1915, cavitation was causing maintenance problems in outlet works of projects owned by the Bureau of Reclamation. In 1941, the first major damage was experienced with open channel flow. After four months of operation of the Arizona spillway tunnel at Hoover dam, a large hole developed in the concrete lining. It was 34 m long, 19 m wide, and had a maximum depth of 11 m. At the time, cavitation was only considered to be one of six possible causes of the damage[1]. We now know that the cavitation was the principal cause of the damage. The development of aeration slots to protect the flow surface was unsuccessful[2].

The next major damage to a spillway tunnel owned by Burec occurred in July 1967. A damaged area, 38 m long, 11 m wide, and up to 2 m deep was discovered following a flood which passed through the tunnel spillway of the Yellowtail dam. Model studies were used to develop an aeration slot which remained free of water at all discharges. Subsequent field tests proved the efficacy of the aeration slot, and subsequently aeration has been applied to almost all structures in which it is thought that cavitation might occur. The location of the aeration slot, and, in fact, the need for an aeration slot, are often not investigated systematically.

A method has now been devised to predict the inception of cavitation on chutes and spillways, and to provide a rough estimate of the possibility of damage based on experience curves derived from Burec's structures.

It is well known that, when the pressure of a fluid reaches vapour pressure, cavities will form in the fluid. This process is known as vaporous cavitation. The formation of vaporous cavitation can be specified by the following dimensionless parameter:

$$\sigma=(p_0-p_V)/(\rho V^2/2) \quad \ldots \quad (1)$$

The reference velocity and pressure can be measured at a number of different points. For example, with sudden into-the-flow offsets, the reference point may be measured upstream of the offset outside the boundary layer, immediately upstream of the offset and at the maximum height of the offset, and outside the boundary layer in the plane of the offset. In each case, the reference pressure is greater than the vapour pressure. Thus, the magnitude of σ when cavitation begins is greater than zero. A typical value of σ for a 90° offset is about 1.8. If σ is greater than 1.8, cavitation will not occur. If σ is less than 1.8, cavitation will occur and the extent of the cavitation increases as σ decreases.

Arndt[4] has found that the value of σ which describes the inception of cavitation for isolated roughnesses is a function of the shape of the offset, the height of the offset in relation to the boundary layer thickness, and the Reynolds number based on the element height. With triangular elements having vertical upstream faces, the correlationship is:

$$\sigma_i=0.152(h/\delta)^{0.361}(V_0/\upsilon)^{0.196} \quad \ldots \quad (2)$$

Arndt also studied the cavitation characteristics of uniformly rough surfaces. The incipient cavitation index in this case was found to be:

$$\sigma_i=16C_f=16\tau/(\rho V_0^2/2) \quad \ldots \quad (3)$$

The case of small isolated roughness near a uniformly rough surface has not been studied. Nevertheless, the preceding equations are sufficient to study the cavitation potential of flow in chutes and spillways.

One method of determining the cavitation potential for a chute or spillway is to calculate a drawdown curve for a series of flow rates. From each curve, the piezometric pressure for various stations can be calculated. The slope correction on steep slopes is:

$$p_0/\gamma=d\cos\theta \quad \ldots \quad (4)$$

If the flow is over a boundary which has a vertical curvature, then the piezometric pressure must also be corrected for the centrifugal force. The piezometric pressure accounting for both slope and centrifugal force is given by:

$$p_0/\gamma=d\cos\theta+(d/g)(V_m^2/r) \quad \ldots \quad (5)$$

If the boundary curvature is upward (concave), the sign of the radius of curvature is positive. If the curvature is convex, the sign of the radius of curvature is negative.

Substitution of the appropriate piezometric pressures

Notations

d	=	depth measured normal to flow surface
g	=	gravitational acceleration
h	=	height of offset
p_0	=	reference pressure
p_V	=	vapour pressure of fluid
r	=	radius of curvature of the boundary
C_f	=	skin friction coefficient
V	=	reference velocity
V_0	=	velocity outside of boundary layer in plane of offset
V_m	=	mean velocity
δ	=	boundary water thickness
υ	=	kinematic viscosity
σ_i	=	incipient cavitation index
τ	=	wall shear thickness
ρ	=	water density
θ	=	bottom slope
γ	=	specific force of water
σ	=	cavitation index

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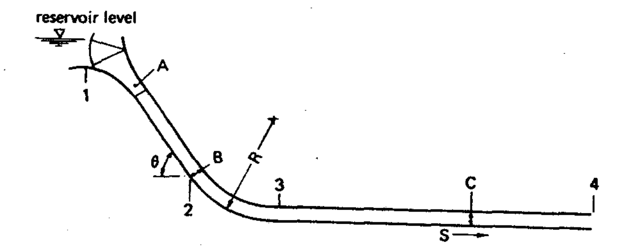

	Blue Mesa	Flaming Gorge	Glen Canyon*	Hoover**	Yellowtail
station (m)					
1	0	0	0	0	0
2	59.5	78.2	99.4	149.4	89.9
3	99.7	127.5	186.5	201.7	162.0
4	375.6	198.1	516.9	659.1	528.2
reservoir elevation (m)					
	110.61	133.91	176.00	181.44	152.80
1	101.01	122.03	156.80	176.56	133.29
2	31.15	26.70	46.65	26.01	43.70
3	9.35	0.71	1.16	1.51	6.00
4	0.00	0.00	0.00	0.00	0.00
diameter (m)					
A	7.52	8.08	14.71	18.29	12.34
B	6.40	5.49	12.50	15.24	9.75
C	6.40	5.49	12.50	15.24	9.75
design discharge (m^3/s)	955	815	3910	5665	2605
θ	55°	55°	55°	50°	55°
R(m)	51.21	60.96	106.68	68.58	88.39
S	0.03388	0.01	0.0035	0.00329	0.004

* Two identical tunnels.
** Two similar tunnels; only that on the Arizona side of the Colorado river has operated for extended periods.

Fig. 1. Comparison of tunnel spillways.

and velocities into Eq. (1) allows the cavitation potential to be calculated for each point on the chute or spillway. If σ is greater than 1.8, cavitation will not occur. If σ is less than 1.8, the height of offset which could cause cavitation can be calculated from Eq. (2). In this computation, some reasonable estimate for the boundary layer thickness must be made. A sufficiently accurate approximation is:

$$\delta = 0.38\upsilon/V_m \qquad \ldots \quad (6)$$

Eq. 3 should also be calculated because if $\sigma < \sigma_i$, then the surface is sufficiently rough to cavitate.

In practice, it will be found that the height of the offset necessary to produce cavitation will be less than 3 mm in structures having flow velocities greater than about 25 m/s. Often no damage is experienced in structures where flow velocities exceed 25 m/s and the offsets are greater than 3 mm. Obviously, this apparent contradiction must be examined closely.

The potential for a surface to be damaged by cavitation depends on: the type of roughness which causes the cavitation; the absolute magnitude of the flow velocity; the air content of the water; the length of time the cavitation occurs; and, the resistance of the surface to damage. With these many variables, correlationships are possible only for rather restricted problem classes. One of these classes is that of circular spillway tunnels, constructed from concrete, built to specifications that are strict enough to yield relatively good flow surfaces.

Five of Burec's dams have tunnel spillways with operating histories which allow one to derive some general guidelines relating to cavitation damage; these are Blue Mesa, Flaming Gorge, Glen Canyon, Hoover, and Yellowtail (see Fig. 1). It should be noted that these are all constructed from the same material (concrete), have approximately the same range of flow velocities (32-43 m/s), and in all probability pass water with approximately the same air content. Blue Mesa is the only exception regarding air content; its flow is controlled by a vertical slide gate. The gate slots cause high degrees of air entrainment at the spillway crest. The flows in the other spillways are controlled by radial gates, and the flow over these crests is almost as smooth as glass.

The parameters of time of operation and the local cavitation index are the two most significant parameters influencing the damage (Fig. 2). The data can be separated into three main types: incipient damage, minor damage, and major damage. Incipient damage is defined as any holes that require special care to discover. Major damage refers to holes greater than 1 m deep. Minor damage refers to holes between incipient and major damage. Although the criterion is subjective, the data can be readily separated into these three categories.

If it has been determined that damage will occur during a certain cumulative operating time for the structure, one possible course of action is to grind all sudden changes in profile to a chamfer which will not cavitate. Data collected by Colgate[5] and by Jin[6] can be used to estimate the required chamfer. Their data were obtained with essentially no boundary layer and, therefore, their results are conservative. They found, for a run to height ratio (*R*/*h*) greater than 5, the incipient cavitation index is given

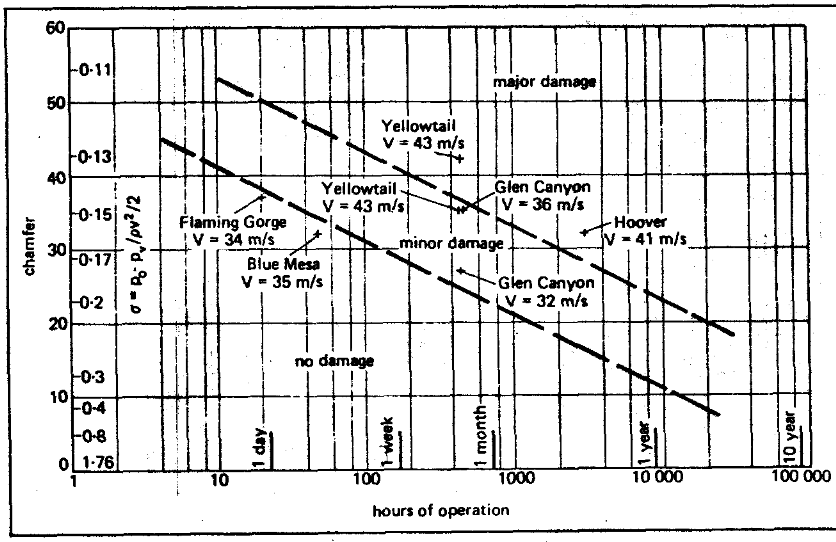

Fig. 2. Cavitation damage in spillway tunnels.

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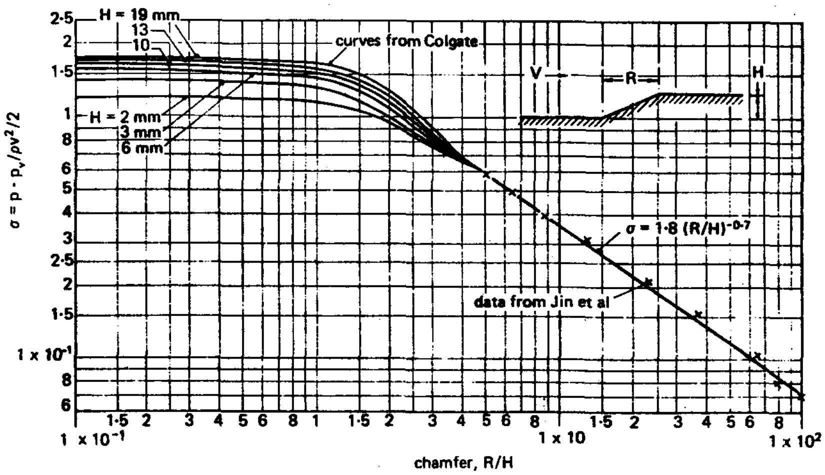

Fig. 3. Incipient cavitation with into-the-flow chamfers.

by:

$$\sigma_i = 1.8(R/H)^{-0.7} \qquad \dots \quad (7)$$

For ratios less than 5, the index is a function of the offset height, Fig. 3. The chamfer values have been included on the abscissa of Fig. 2.

The relationships given above can be used not only to assist in the location of aeration slots but also to guide the designer in knowing where strict tolerances are necessary. As an example, the Glen Canyon tunnel spillways can be considered. To facilitate analysis, a computer program was written to carry out the water surface computations and includes the equations given above. The chamfers required to eliminate cavitation are shown in Fig. 4 for a variety of flow rates.

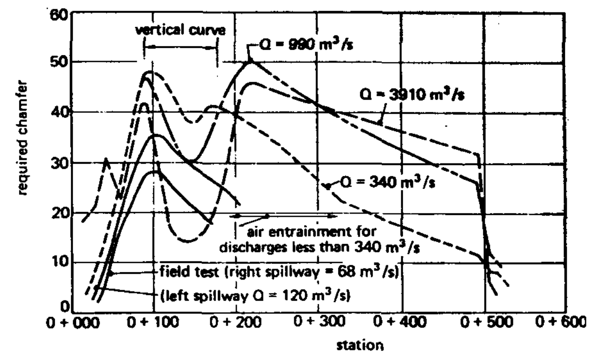

Fig. 4. Cavitation characteristics for the Glen Canyon dam spillway tunnels.

The results of the study indicate that the Glen Canyon spillway tunnels are very susceptible to cavitation. The heights of offsets required to produce cavitation are negligible. However, with respect to producing damaging cavitation at flow rates less than 340 m^3/s, the portion of the tunnels between stations 65 and 180 need special attention. All offsets up to station 65 only need to be ground to a chamfer of 1:20. A flow rate of 990 m^3/s is the discharge most likely to cause major damage. This damage will occur after the tunnel has operated for a cumulative period of time exceeding only 25 h at the most destructive flow rate. At a lower flow rate of 340 m^3/s, the tunnel could operate for almost a month without sustaining major damage. It is obvious that damage to the spillway tunnels at Glen Canyon cannot be avoided by rigid specifications on the allowable flow surface tolerances if the spillways are operated at large discharges. A remedial measure which will protect the tunnels will be discussed in a subsequent article.

In conclusion, it has been shown that a rather simplified analysis can lead to a method of predicting the formation of cavitation in tunnel spillways. This has been expanded, using prototype experience, to produce curves which predict how long it takes for damage to occur if cavitation is present in a tunnel spillway. These results can be used to indicate where surface tolerances can be relaxed. In addition, areas can be delineated in which the surface tolerance required to eliminate damage cannot be achieved physically. In these areas, the use of air grooves may be a practical remedial measure.

Although the results of this study were derived primarily from tunnel spillway experience, preliminary investigations indicate that the curves are also applicable to chutes.

More field experience is needed to define better the shape of the damage curve (Fig. 3). Obviously, the inception of damage curves should be asymptotic with the σ = 1.76 or chamfer = 0 line. Contributions from the profession would be welcome in these areas. □

Damage caused by cavitation downstream in the vertical bend of the spillway at the Yellowtail dam.

spillway

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